Top Physics at LHC

thinkshop^2
top-quark physics for Run II & beyond

Fermi National
Accelerator Laboratory
November 10-12, 2000

Outline

- The LHC machine
- Why study top at LHC
- Top production & tagging at LHC
- $t\bar{t}$ event reconstruction
- Top mass measurement
- Highlights of other studies
  - spin correlations & CP violation
  - rare decays
  - Single top physics $\Rightarrow$ see talk of D.ONeil
- Summary

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10 November 2000

References

- ATLAS Physics TDR
  - CERN-LHCC 99-14/15; *http://atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html*
- CMS Technical proposal
- various notes from both experiments
- 1999 LHC Workshop on Standard Model Physics (and more)
  - CERN 2000-004, 9 May 2000
  - top physics chapter: *"http://arXiv.org/abs/hep-ph/0003033"* and references therein

Please note:

- Both ATLAS & CMS experiments have performed studies for most of the topics discussed here. For the analyses that I discuss, the numbers are from ATLAS unless stated otherwise

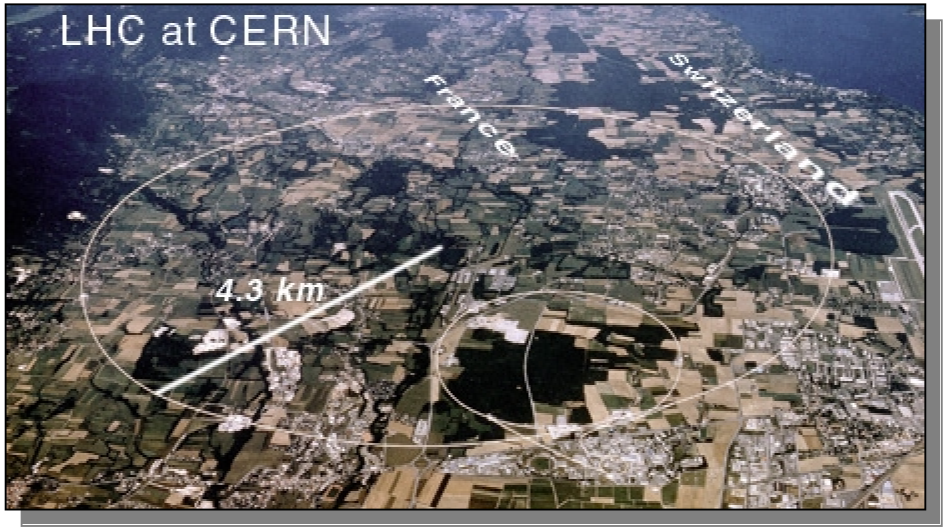
- many thanks to all the colleagues who provided material for this talk
  - in particular:
    - M. Cobal, P. Grenier, A. Karchilava, D. Pallin, J. Parsons, P. Roy, V. Simak, S.Sonnenshein

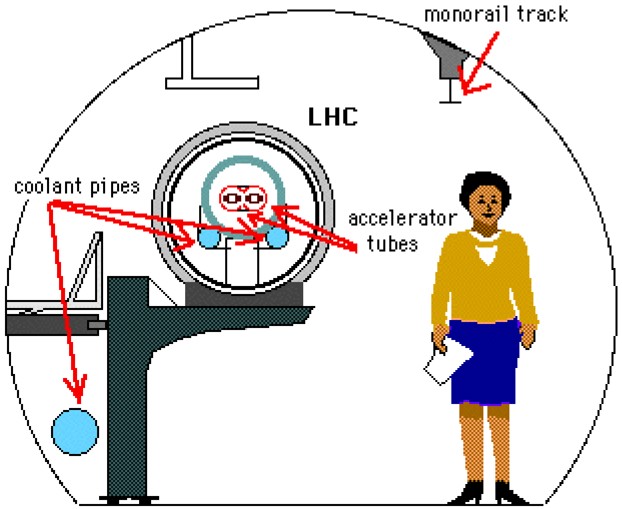
The LHC machine

LHC parameters - pp collisions

Operating beam energy E	7 TeV
Bunch spacing	24.95 ns; 7.48 m
Number of all/full bunches	3564/2835
Design luminosity L	10^{34} cm^{-2} s^{-1}
Luminosity lifetime	10 h
Number of interactions/beam crossing	23
Bunch radius $\sigma_x=\sigma_y$	16 µm
RMS length of luminous region	56 mm
Total crossing angle	300 µrad
Stability of beam size during fill	few µm
Stability of beam size from fill to fill	<50% change
Stability of transverse beam position during fill	<50 µm
Stability of transverse beam position from fill to fill	<50 µm

First collisions @10^{33} expected in ~2005

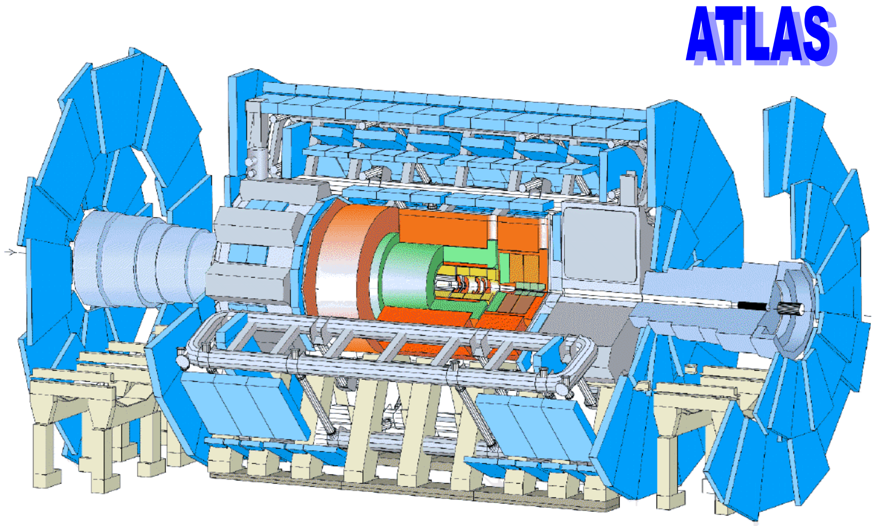




...The LHC machine

Stringent detector requirements

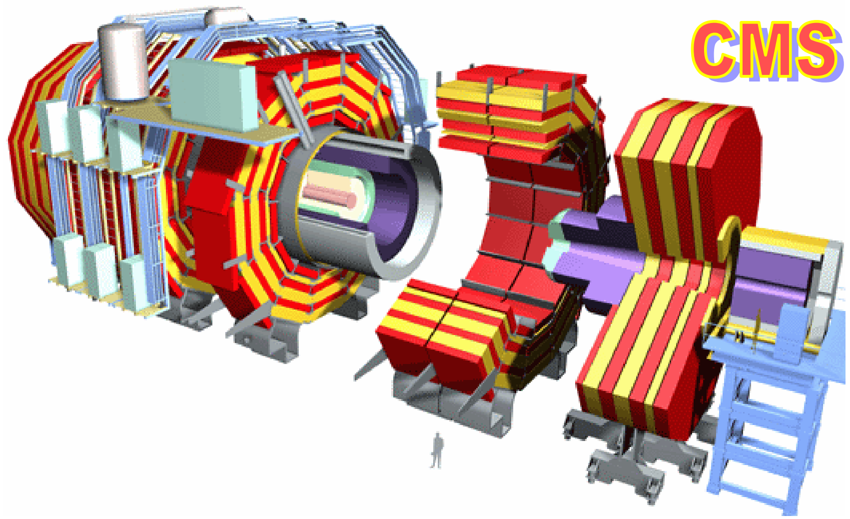
- bunch crossing / 25 ns
  - fast detectors, fully pipelined readout
- large number of tracks in the detector
  - good detector granularity, keep occupancy low, minimize pile-up effects
- high radiation environment



very large systems, eg. ATLAS:

- $\sim 10^7$ channels for the ID
- $\sim 10^5$ channels for calorimeter
- $\sim 10^6$ channels for the μ-spectrometer

it will require substantial effort to calibrate and maintain for >10 years!



...The LHC machine

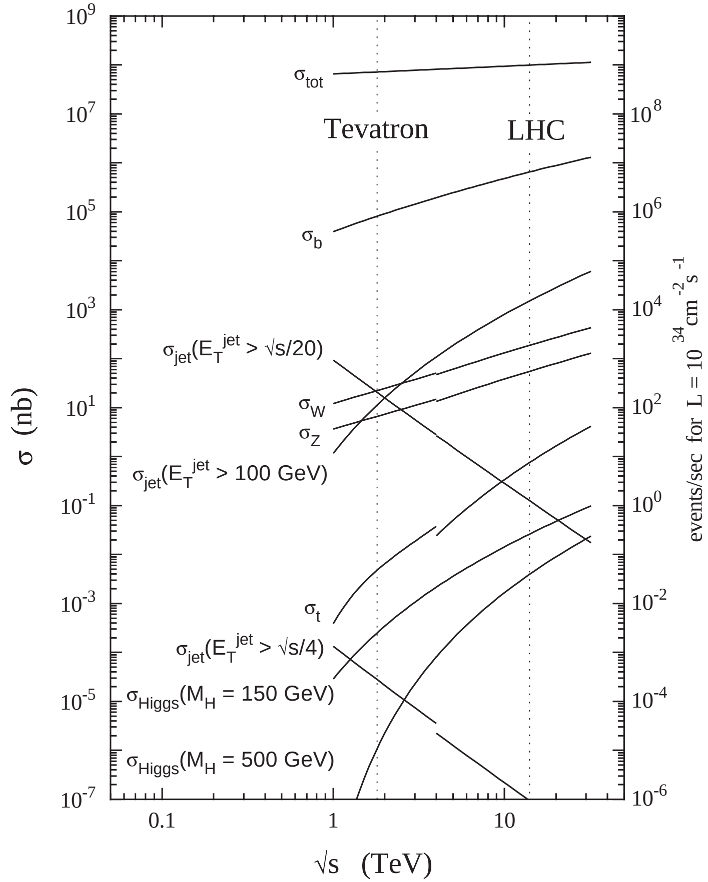
Event production rates

- for 70 mb total cross-section

  $\rightarrow 10^9$ interactions/second @ $10^{34}\ cm^{-2}\ s^{-1}$

  but interesting physics processes many orders of magnitude lower

  - for example:
    - Higgs production: 10^{-2} (10^{-1})Hz for m_H= 500(100) GeV
    - top production: 10 Hz
    - W production: ~2 KHz



- requires a highly selective trigger
  - ~ 10^7 rejection power
- implemented in several (2/3) layers

  Level 1 : ~75(100)KHz

  $\Downarrow$

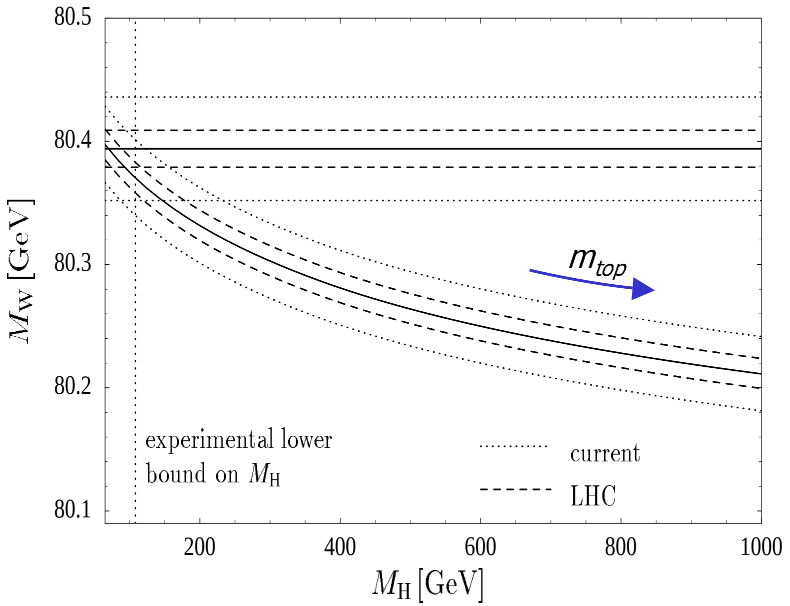
  Event filter/data storage: ~100 Hz

Why study top physics at LHC

- the top quark exists and will be copiously produced at LHC
- it's properties can be studied with good accuracy due to large statistics available

- several questions to answer:
  - why m_t so different from other quarks?
    - is it really a SM-like particle?
  - study it's production, couplings and decays

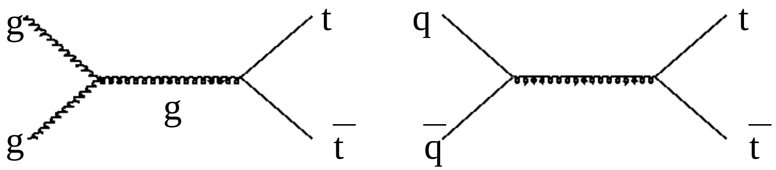
  any deviation from SM values will be a sign of new physics
- in the SM, the m_t, m_W and m_H are coupled:
  - $\Delta m_W \approx 0.7 \times 10^{-2} \Delta m_t$ to get similar errors
- top quark events are a major source of background for many physics searches
- important sample for absolute jet energy calibration



- δm_W=±0.042GeV(current), ±0.015GeV(LHC)

Top production & tagging at LHC

- t-pair production mainly through gg-fusion



~90% 10%

- The LHC machine is a real **top factory!!!**
- NLO: $\sigma(t\bar{t})$ ~830 pb
- low luminosity 10 fb^{-1}($\rightarrow$1 year at 10^{33} cm^{-2} s^{-1})
  - ~ 8 million $t\bar{t}$ pairs

  in addition:
  - ~ 3 million single top events

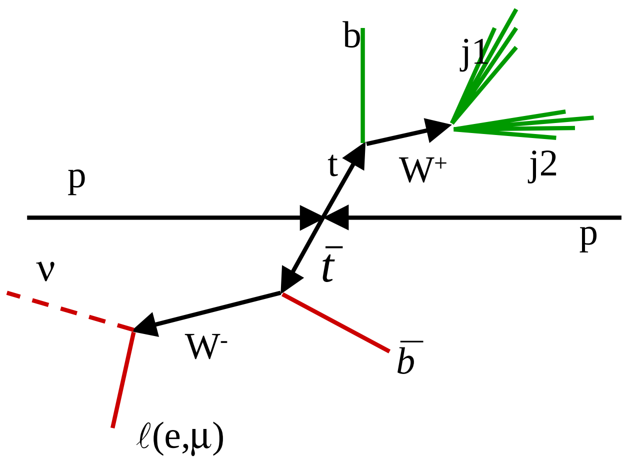
  1 top event per second at LHC startup!
- no problem with statistics
- background can be kept small in most of the cases

...Top production & tagging at LHC

top events can be easily reconstructed in single/double lepton channels with good statistics and small background contamination

single lepton + jets channel

- ~29.6% Br, ~2.5M events/year
- isolated lepton for trigger (p_T>20 GeV)
- selection cuts:
  - lepton: p_T> 20 GeV, $|\eta|$< 2.5
  - E_T^{miss} > 20 GeV
  - jets: ≥ 4, p_T> 20 GeV, $|\eta|$< 5, ΔR=0.7
  - b-tag jets: ≥ 1
  - → 33.3% efficiency,
    - ~ 820 000 $t\bar{t}$ events/year,
    - S/B(mainly W+jets) ~ 18.6

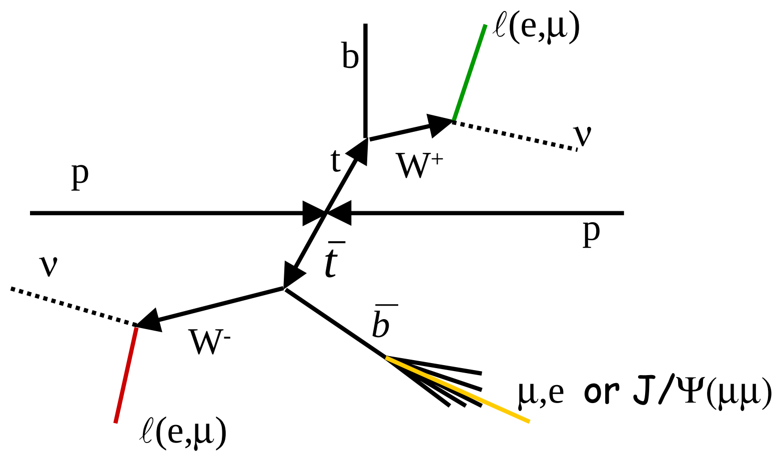


- sub-samples can also be exploited for specific studies
  - e.g. high p_T sample for top mass measurement (see later...)

...Top production & tagging at LHC

di-lepton channel

- ~4.9% Br, ~400 000 events/year
- selection cuts:
  - two opposite sign leptons:
    - p_T> 35(20) GeV, $|\eta|$< 2.5
  - E_T^{miss} > 40 GeV
  - jets: ≥ 2, p_T> 25 GeV, $|\eta|$< 5, ΔR=0.7
  - like-flavour case (e^+e^-, $\mu^+\mu^-$)
    - $|m_{\ell\ell}$ - $M_Z|$ > 10 GeV
  - → ~ 80 000 $t\bar{t}$ events/year, S/B~10
  - b-tag jets: ≥ 1
  - → ~ 58 000 $t\bar{t}$ events/year, S/B~50



- again sub-samples can also be exploited for specific studies
  - e.g. J/Ψ sample for top mass measurement (see later...)

...Top production & tagging at LHC

multi-jet channel

- ~44.4% Br, ~3.7M events/year
- but huge background
  - QCD multi-jet
  - not easy to have an efficient trigger
    - multi-jet + total E_T threshold
- selection cuts:
  - jets: ≥ 6, p_T> 15 GeV, |η|< 3, ΔR=0.7
  - b-tag jets: ≥ 2, |η|< 2.5
  - sum P_T^{jets} >200 GeV

  → 19.3% signal efficiency,

  only 0.29% of QCD multi-jets remaining
- S/B ~ 1/57 assuming:
  - σ(QCD multi-jet) = 1.4×10^{-3} mb for P_T^{hp} >100 GeV

- further improvement possible using event topology and kinematic cuts
  - W reconstruction
  - both t & $\bar{t}$ reconstruction

  → S/B improved to ~ 1/8

  in m_t [130, 200] GeV
  - harder jet cuts: p_T> 25 GeV

  → S/B improves to ~ 1/6

  in m_t [130, 200] GeV

- it might be possible to extract the signal from the background,

but

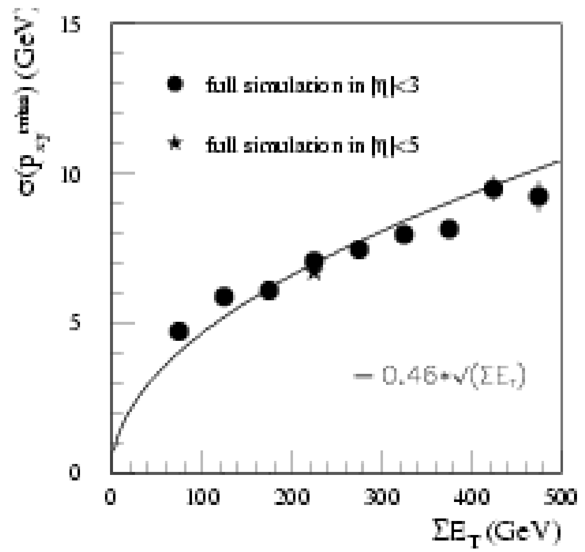
- it will suffer from the uncertainties in the multi-jet rates and topologies.

Relevant detector performance

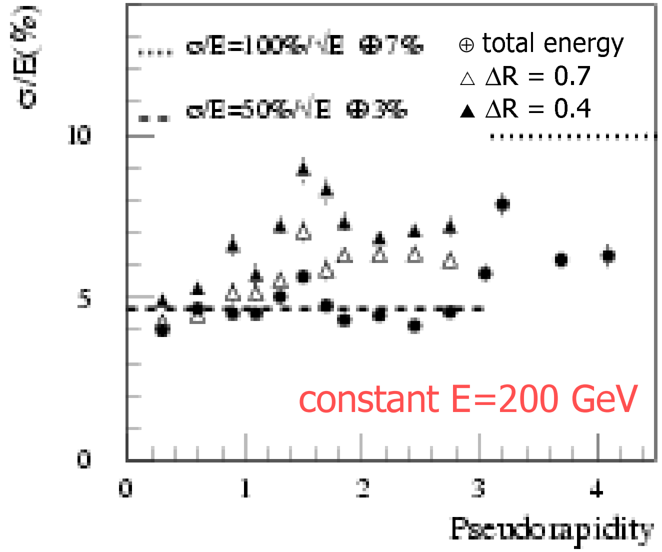
Jet resolution

- good jet coverage up to $|\eta| \lesssim 5$
- and good E_T^{miss} resolution

E_T^{miss} resolution - ATLAS



Jet resolution - ATLAS



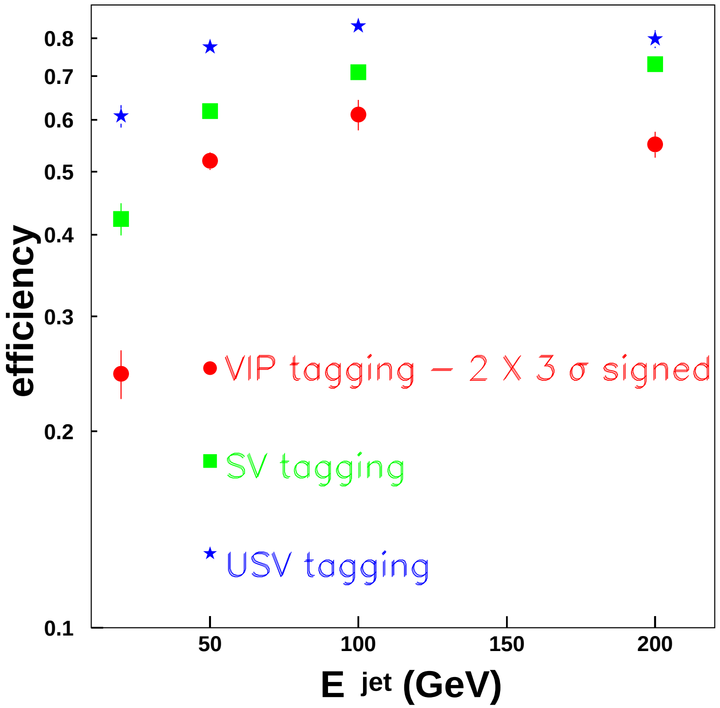
	Barrel region η=0.3		End-cap region η=2.45	
	a (% GeV$^{1/2}$)	b(%)	a (% GeV$^{1/2}$)	b(%)
Full calo	48.2±0.9	1.8±0.1	55.0±2.5	2.2±0.2
ΔR = 0.7	52.3±1.1	1.7±0.1	64.2±2.4	3.6±0.2
ΔR = 0.4	62.4±1.4	1.7±0.2	68.4±3.4	4.4±0.2

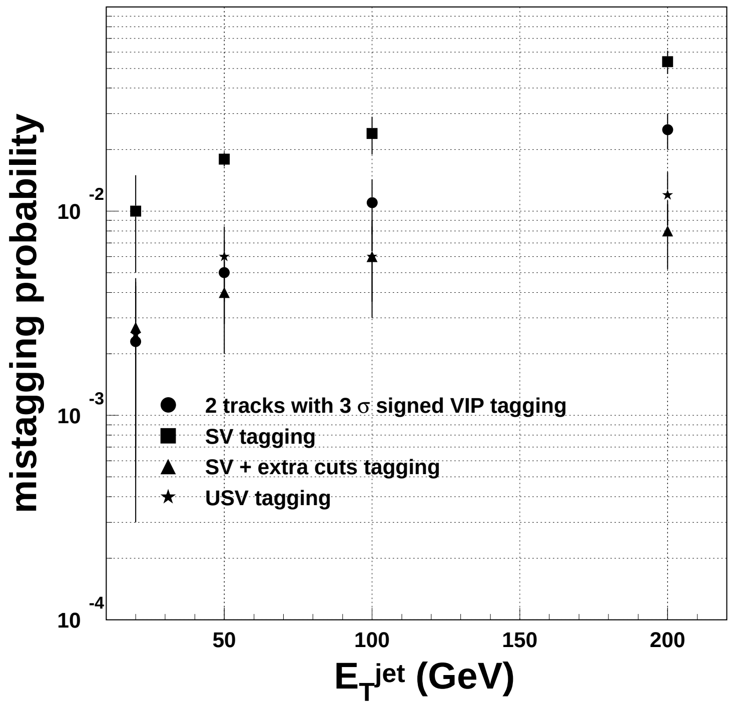
Relevant detector performance

b-jet tagging

- extended coverage: $|\eta|<2.5$
  - silicon tracker (+TRT for ATLAS)
  - b-jet layers (pixel detectors)
- typical values:
  - ε_b ~60%
  - fake tag: 10%(c-jets), 1% (u,d,s-jets)

b-jet tagging - CMS





$t\bar{t}$ event reconstruction

Search for resonances decaying into $t\bar{t}$

- expected in many theoretical models
  - in SM:
    - H$\rightarrow t\bar{t}$ if it's kinematically allowed, but difficult to observe a Higgs peak above the large $t\bar{t}$ continuum background
  - in MSSM:
    - if m_A, $m_H > 2m_t$ then Br($H/A\rightarrow t\bar{t}$) ~ 100% for $\tan\beta$ ~ 1, but could be suppressed due to interference with the standard $gg \rightarrow t\bar{t}$ production
  - in Technicolor: eg. color octet techni-eta (η_8)
  - Topcolor or fourth generation heavy quarkonia decaying to $t\bar{t}$

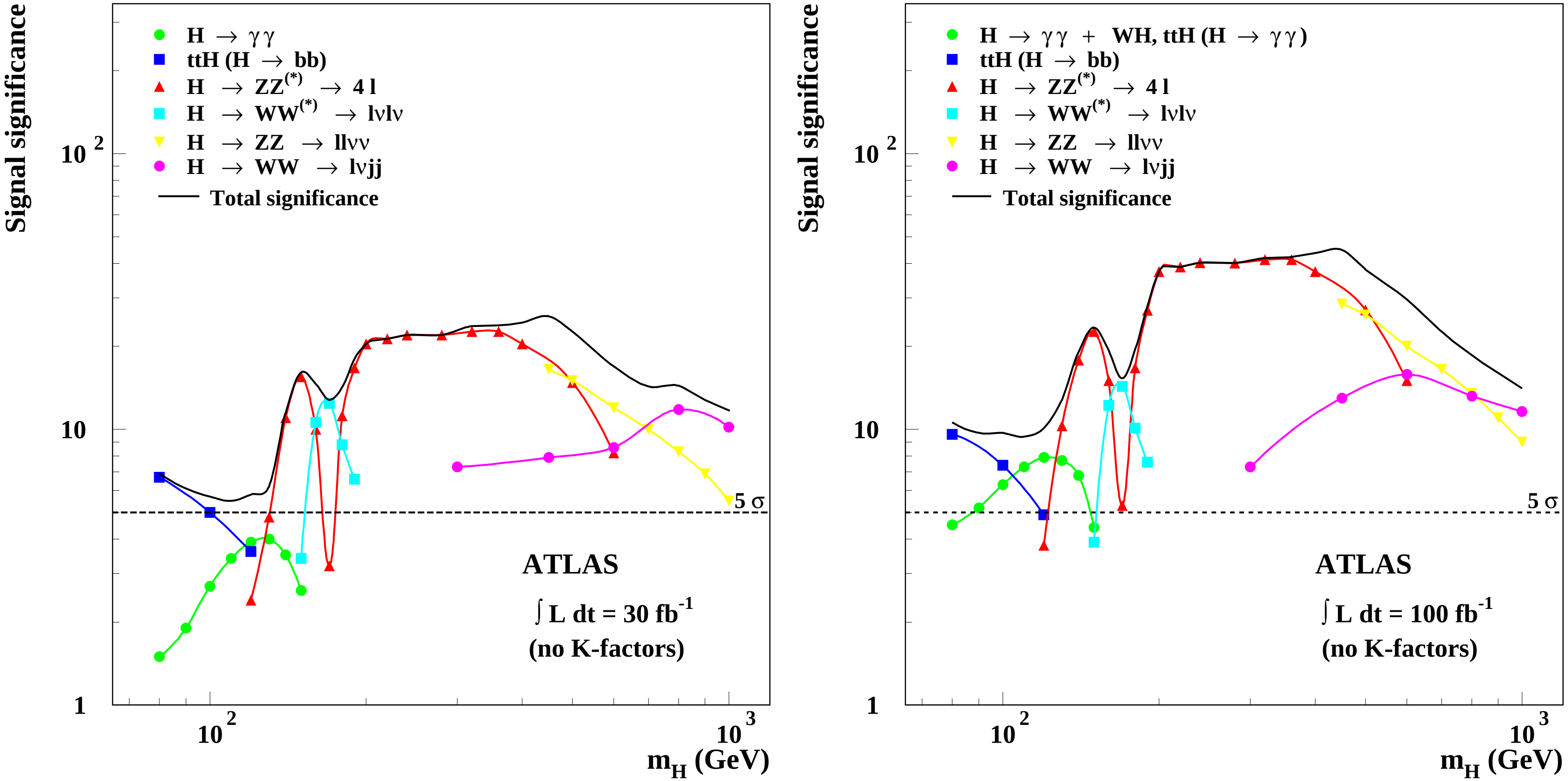
Associated Higgs production $t\bar{t}H$

- possible to study both top quark and Higgs boson at LHC
- important channel in the intermediate mass region 100-130 GeV

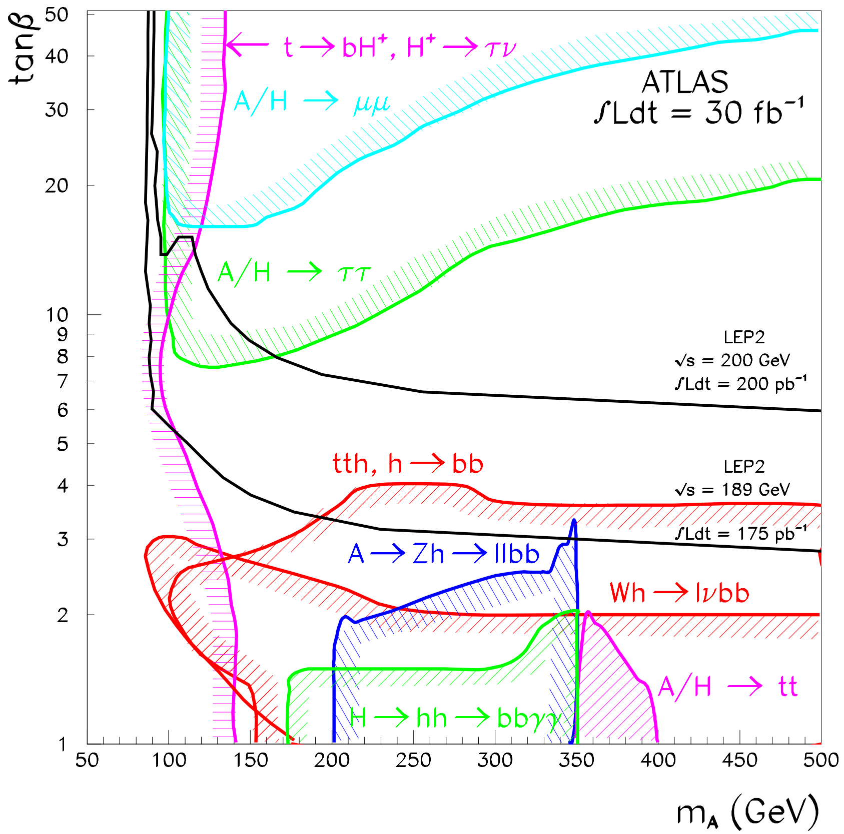
Measurement of top Yukawa coupling

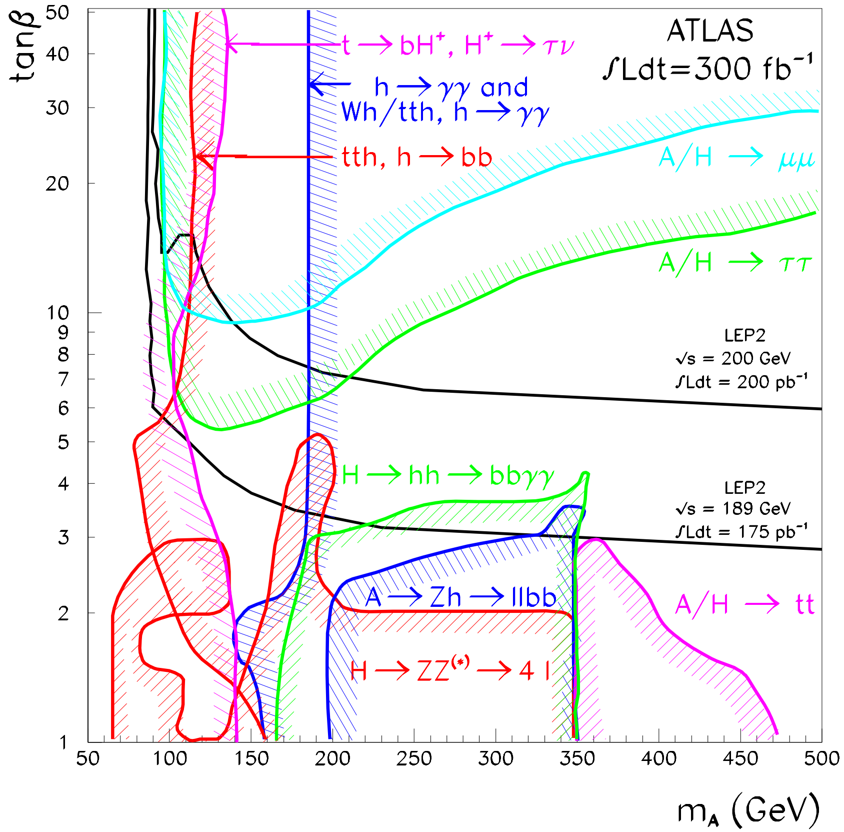
- important SM parameter

...$t\bar{t}$ event reconstruction



...$t\bar{t}$ event reconstruction





...$t\bar{t}$ event reconstruction

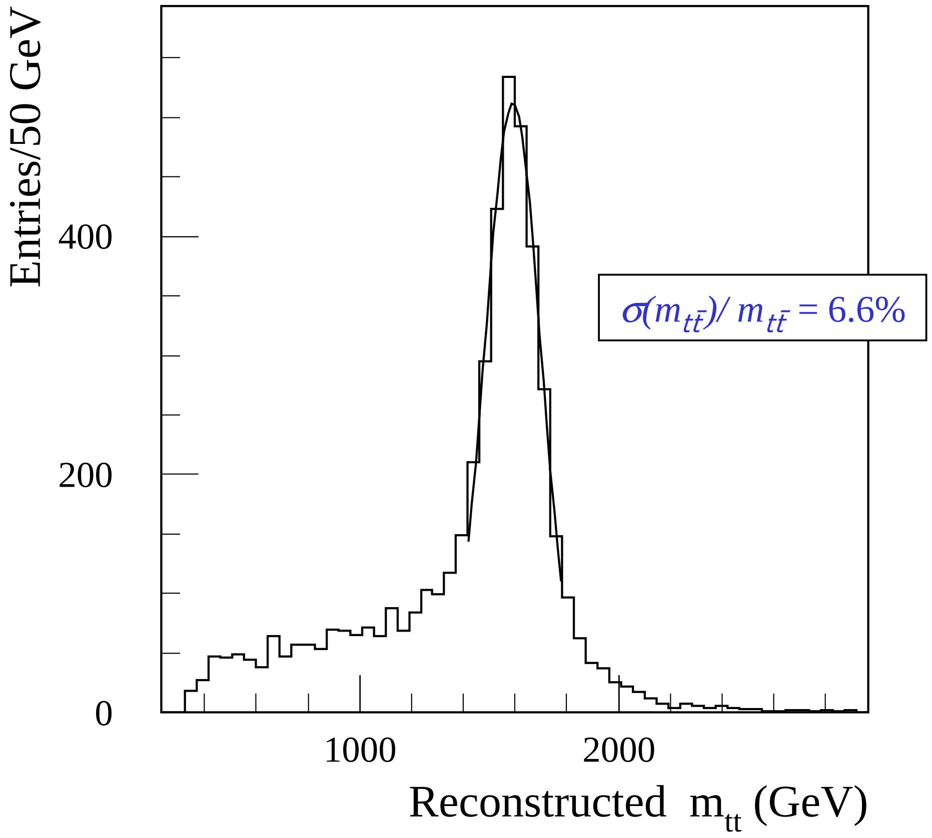
Search for resonances decaying into $t\bar{t}$

single lepton+jets channel

- selection cuts:
  - isolated lepton: $p_T > 20$ GeV, $|\eta| < 2.5$
  - $E_T^{miss} > 20$ GeV
  - $4 \leq N_{jets} \leq 10$, $p_T > 20$ GeV
  - b-tag jets: ≥ 1, $p_T > 20$ GeV, $|\eta| < 3.2$
- reconstruct ν momentum
  - resolve quadratic ambiguity
  - impose M_W constraint
- select combination that minimizes

$$\chi^2 = \frac{(M_{jjb} - m_t)^2}{\sigma^2(M_{jjb})} + \frac{(M_{\ell\nu b} - m_t)^2}{\sigma^2(M_{\ell\nu b})} + \frac{(M_{jj} - M_W)^2}{\sigma^2(M_{jj})}$$

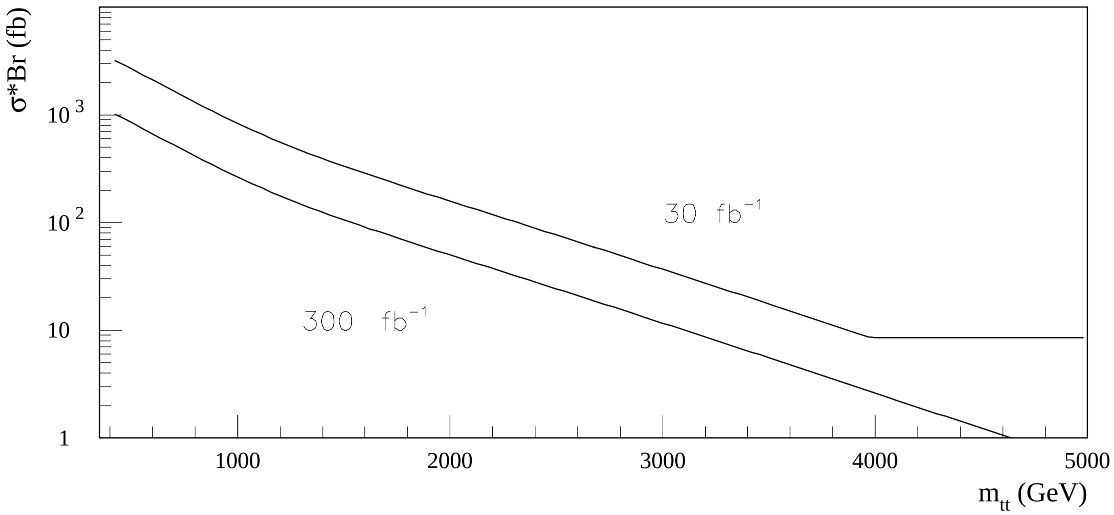
  - for candidates within a 30 GeV window from the nominal mass values



~65% of the events within $\pm 2\sigma$ of the peak

...$t\bar{t}$ event reconstruction - search for resonances $X \to t\bar{t}$

- after cuts, background is dominated by $t\bar{t}$ continuum
- determine the 5σ discovery limit for a "resonance X" of a particular model for a given prediction of $\sigma(X)$, Br($X \to t\bar{t}$) and $\Gamma(X)$
- overall selection efficiency:
  - ~15 - 20 % for resonance masses 400 Gev - 2 TeV

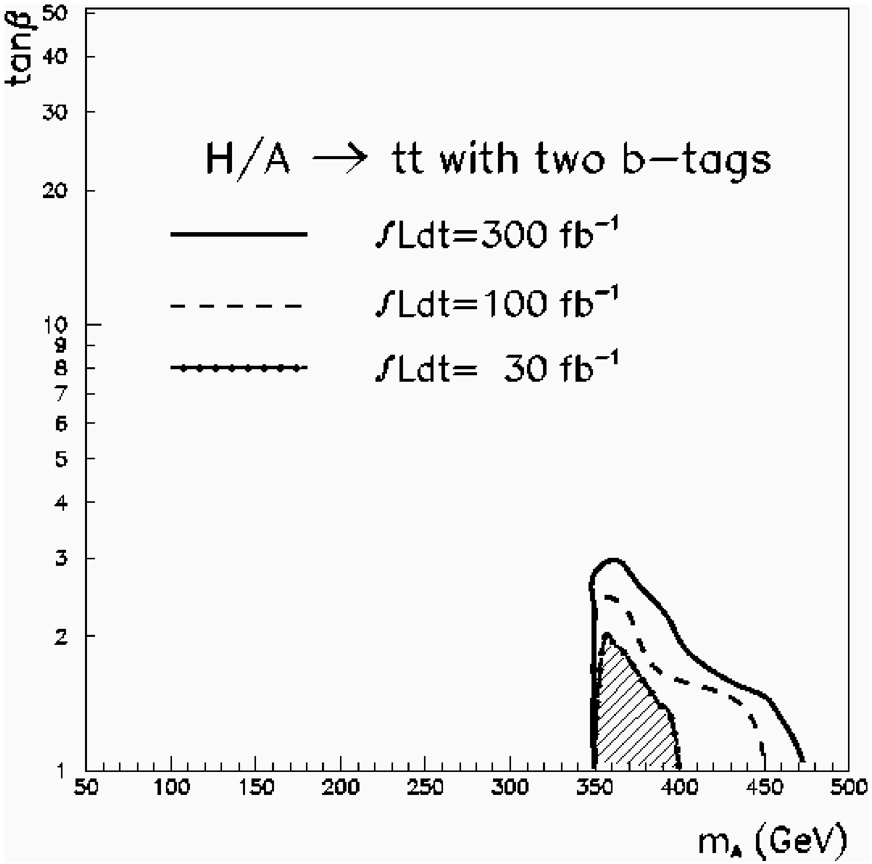


$\mathcal{L}$ (fb^{-1})	Mass m_X(GeV)	$\sigma \times$ Br (fb)
30	500	>2560
	1000	>830
	2000	>160
300	500	>835
	1000	>265
	2000	>50

...$t\bar{t}$ event reconstruction

in MSSM

- consider the case $H/A \rightarrow t\bar{t}$
  - with m_A, $m_H > 2m_t$
  - and $tan\beta = 1$
- in this case the Br is about 100%, but can be severely reduced due to interferences between the gg $\rightarrow$ $H/A \rightarrow t\bar{t}$ amplitude and the usual gluon fusion process: $gg \rightarrow t\bar{t}$
  - increase as the Higgs mass and width increase
- overall sensitivity limited in the 370 - 450 GeV range assuming that the $t\bar{t}$ continuum is well known (1%)



...$t\bar{t}$ event reconstruction

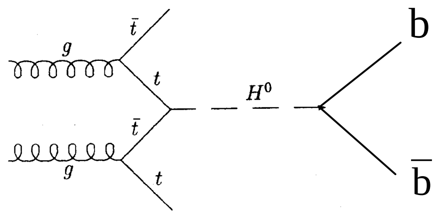
Associated higgs production $t\bar{t}H$

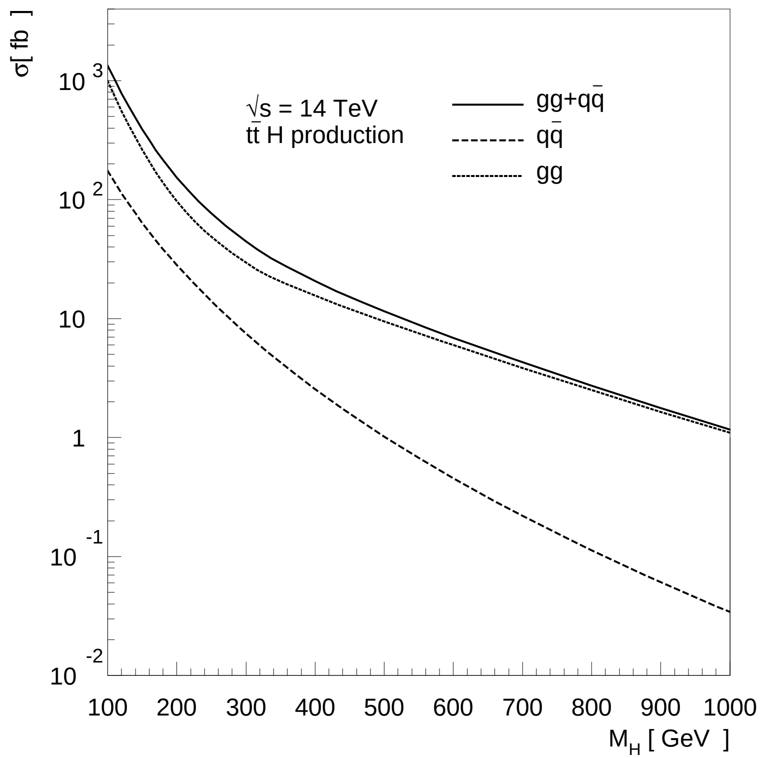
$tH \to (\ell\nu)(jj)bb$ channel

- selection cuts:
  - isolated lepton: p_T > 20 GeV, $|\eta|$< 2.5
  - Njets $\geq$ 6, p_T > 15 GeV
  - 4 b-tag jets, p_T > 15 GeV, $|\eta|$< 2.5
- reconstruct both W:
  - use E_T^{miss} for ν momentum, resolve quadratic ambiguity, impose M_W constraint, select candidates in a $\pm$ 25 GeV window
- select candidate combination which:
  - minimizes:

$$\chi^2 = (m_{jjb} - m_t)^2 + (m_{\ell\nu b} - m_t)^2$$

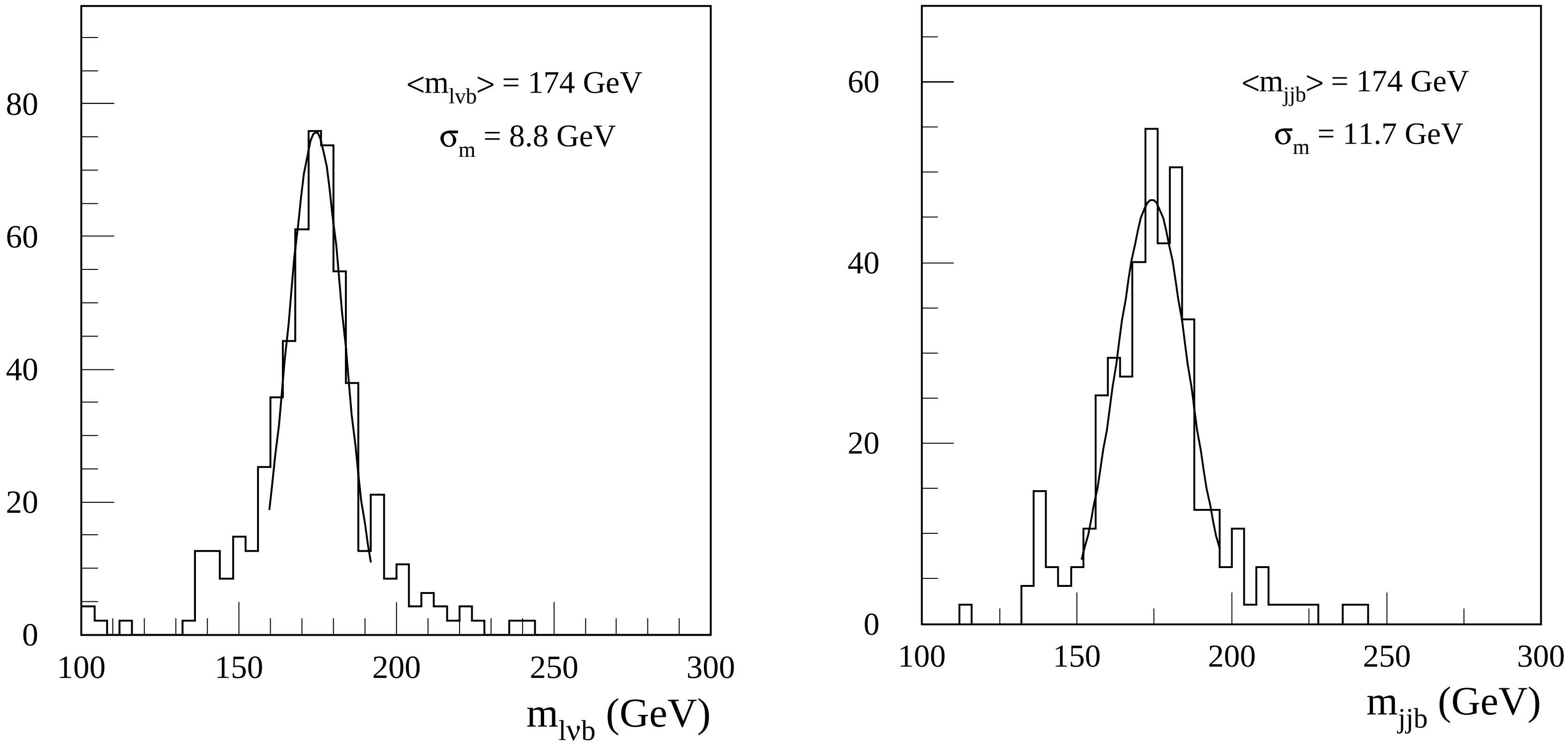
  - and if the reconstructed m_t, $m_{\bar{t}}$ is $\pm 2\sigma$ from the nominal mass





CompHEP, MADGRAPH, HELLAS calculations

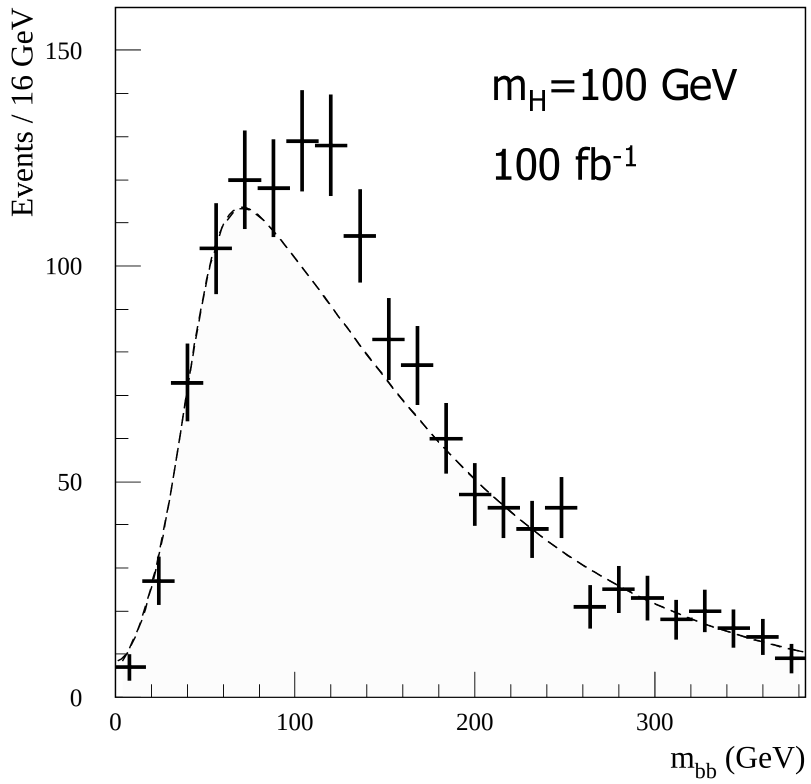
...$t\bar{t}$ event reconstruction - $t\bar{t}H$ associated production



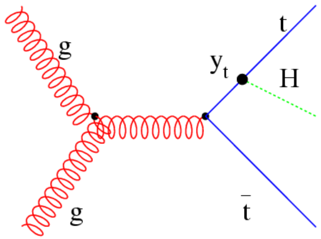
- total acceptance: 1.7% at low luminosity, 0.7% at high luminosity
- main remaining background: $t\bar{t}b\bar{b}$
  - 56% of the total $t\bar{t}$ +jets background

...$t\bar{t}$ event reconstruction - $t\bar{t}H$ associated production

- combine the two remaining b-jets to reconstruct the $H \to b\bar{b}$ decay



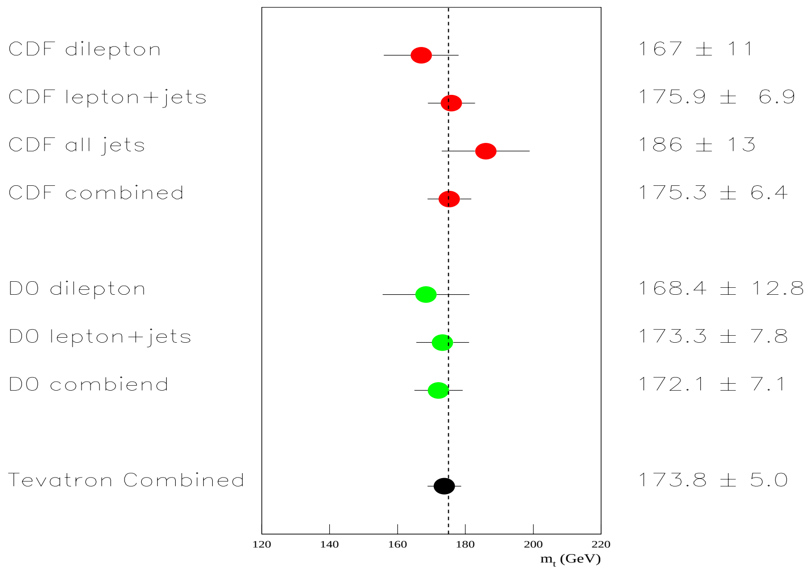
top Yukawa coupling y_t



- for 30 fb^{-1}
  - N_{signal} = 61 events
  - $N_{bcckground}$ = 150 events
  - $\rightarrow \delta y_t$(stat) = 12%
- for 100 fb^{-1}
  - $\rightarrow \delta y_t$(stat) = 5% for m_H = 100 GeV
  - $\rightarrow \delta y_t$(stat) = 10% for m_H = 120 GeV
- systematics can be controlled by comparing to the standard $t\bar{t}$ production

Top mass measurement

- m_t is a fundamental parameter in the SM
- currently is measured to ±5 GeV at the Tevatron Run-I



For Run-II

- larger statistics
- systematic error can be improved
- expected: $\Delta m_t \sim 1\%$

	m_t Uncertainty (GeV)	
	Run-I	**Run-II**
Statistical	5.6	1.3
Jet E-scale	4.0	0.4
Gluon ISR/FSR	3.1	0.7
Detector noise etc.	1.6	0.4
Fit procedure	1.3	0.3
All systematic	5.5	0.9
Total	7.8	1.6

hep-ex/9904019

Can we do equally well or even better at LHC?

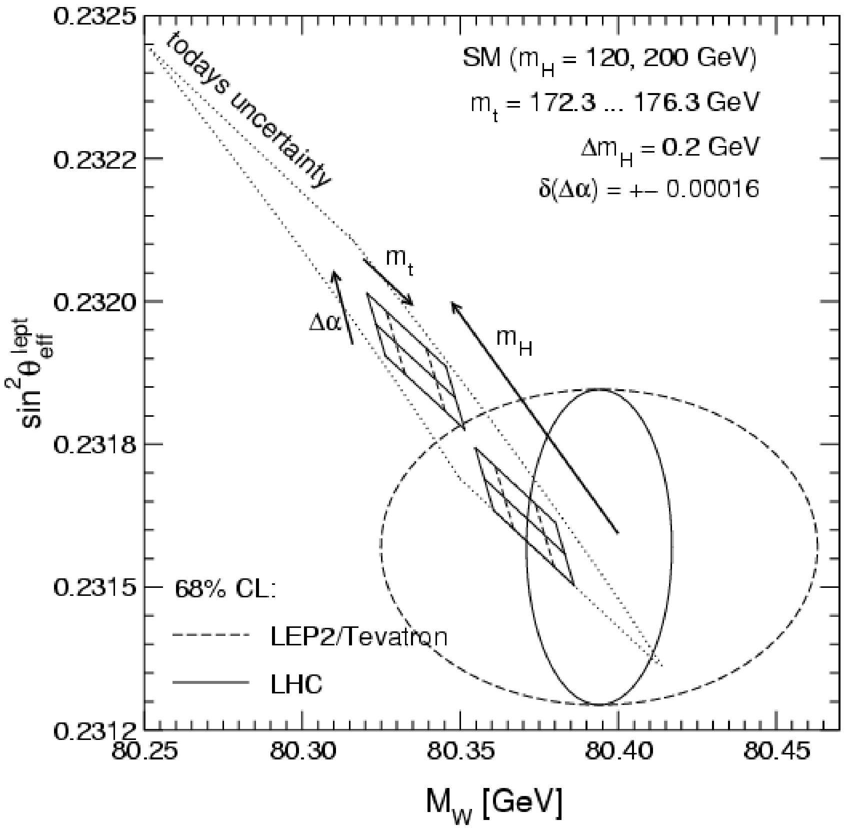
... Top mass measurement

- what is the interest in going from Δm_t = 2 GeV to Δm_t = 1 GeV (<1%)?

present theoretical uncertainty from unknown higher order corrections

	Δ_{theo}	$\delta(\Delta\alpha_{had})$ 0.00016	Δm_t 2 GeV	1 GeV
$\Delta m_W/m_W$(MeV)	6	3.0	12	6.1
$\Delta \sin^2\theta_{eff}^{lept} \times 10^5$	4	5.6	6.1	3.1

- the 1 GeV error in m_t induces an uncertainty about the same as today's theoretical error
- if m_H is known (Tevatron or LHC) the improved accuracy in m_t and m_W leads to a stringent consistency test of the theory



LEP2/Tevatron: δm_W=±30MeV, $\sin^2\theta_{eff}^{lept}$ = 1.7×10^{-4}
LHC: δm_W=±15MeV, $\sin^2\theta_{eff}^{lept}$ = 1.7×10^{-4}

... Top mass measurement

- The large top production rate at LHC allows many different possibilities for measuring the top mass to be exploited
- Several studies up to now by both experiments, highlights will be presented here:

single-lepton+jets channel:

$t\bar{t} \to W^+ b W^- \bar{b} \to (jj)b(\ell\nu)\bar{b}$

- inclusive sample:
  - no selection in the p_T of the top
  - $m_t \equiv m_{jjb} \to$ direct measurement
  - complete event reconstruction
    $\to$ constrained kinematical fit
- high p_T sample: eg. >200 GeV
  - $m_t \equiv \Sigma E_T$ of the calorimeter cells in a cone around the top quark direction

di(multi)-lepton channel:

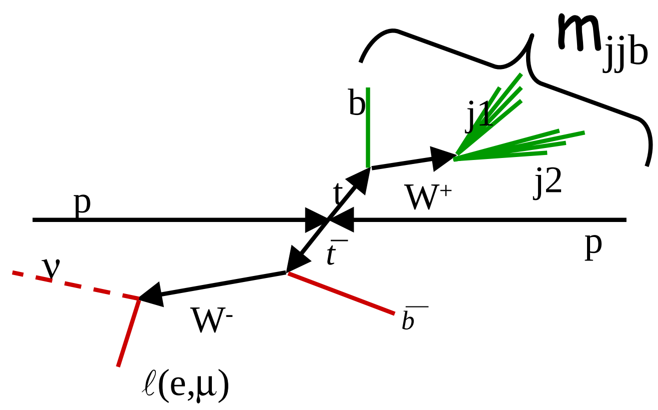
$t\bar{t} \to W^+ b W^- \bar{b} \to (\ell\nu)b(\ell\nu)\bar{b}$

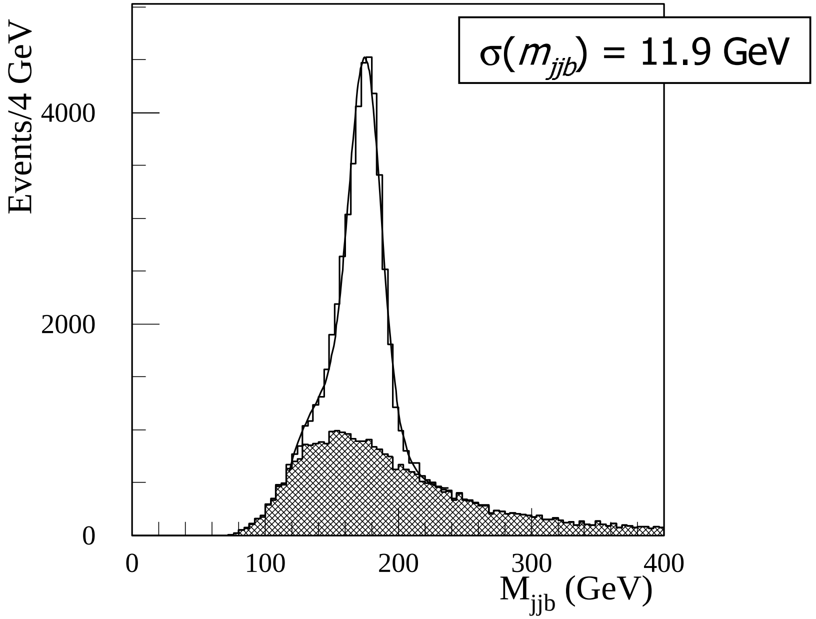
- $m_t \propto$ some observables: e.g. $m_{\ell b}$
- not a direct measurement, depends strongly on the Monte Carlo predictions
- J/Ψ sample:
  - $m_t \propto m_{\ell J/\Psi}$ which shows stronger correlation with m_t
  - can be better modeled by the MC and can lead to smaller syst. errors

...Top mass measurement - single lepton + jets channel

Inclusive Sample

- selection cuts:
  - isolated lepton: P_T > 20 GeV, $|\eta|$ < 2.5
  - E_T^{miss} > 20 GeV
  - jets: ≥ 4, P_T > 40 GeV, $|\eta|$ < 2.5 R = 0.4
  - b-tag jets: ≥ 2
- W reconstruction
  - use non b-tag jets and form m_{jj}
  - select combination with $|m_{jj} - M_W|$ minimum
- top reconstruction
  - combine the W candidate with b-jet
  - evaluate the three-jet invariant mass m_{jjb}
- within ±35 GeV window in m_t
  - ~ 30K events @ 10 fb^{-1}
  - ε=1.2%, purity = 68%, S/B ~ 65
- δm_t(stat) = ± 0.070 GeV @ 10 fb^{-1}
- background dominated by "wrong combinations"



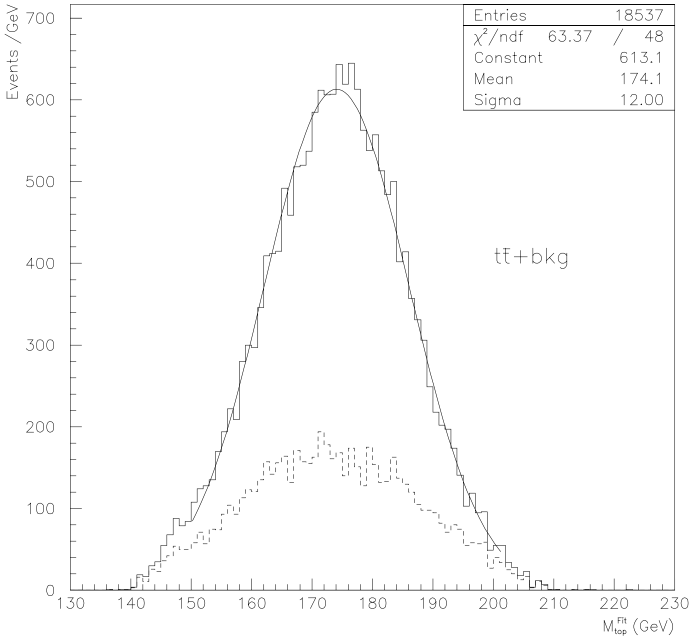


...Top mass measurement - single lepton + jets channel

Inclusive sample - kinematic fit

- reconstruct the $\bar{t}$ decay
  - use E_T^{miss} for ν momentum, impose M_W constraint, keep both solutions
  - select b-jet closest to the isolated lepton (purity ~ 77%)
  - keep event if at least one of the ν solutions gives m_t in the mass window
- 27000 $t\bar{t}$ events @ 10fb-1
  - ε=1.1%, purity = 77%
- kinematic fit (CDF method):
  - use the constraints:
    - $m_{jj} = m_{l\nu} = M_W$ and $m_{jjb} = m_{l\nu b}$
  - choose ν solution with $m_t^{lept} \approx m_t^{had}$
  - minimize the quantity:

$$\chi^2 = \sum_{\substack{jets\\lepton}} \left(\frac{p_T^m - p_T^{fit}}{\sigma_{p_T}}\right)^2 + \sum_{i=x,y} \left(\frac{p_i^m(\nu) - p_i^{fit}(\nu)}{\sigma_{xy}}\right)^2 + \sum_{i=1,2} \left(\left(\frac{m_{top}^j - m_{top}^{fit}}{\sigma_{top}}\right)^2 + \left(\frac{m_W^j - M_W}{\sigma_W}\right)^2 \right)$$



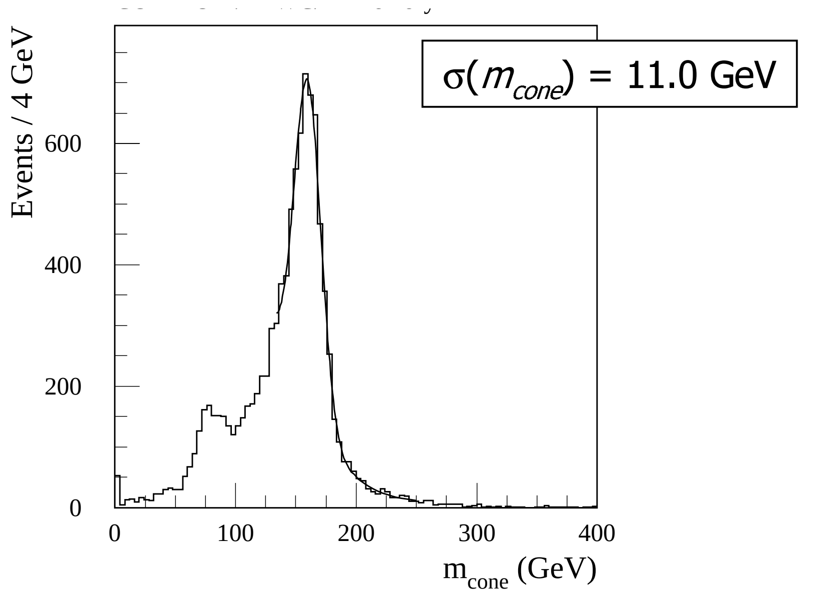
- Work in progress to understand the χ^2 dependence on m_t^{reco}
  - major component: b-jet calibration and reconstructed direction

...Top mass measurement - single lepton + jets channel

High P_T (>200 GeV) sample

- better control of the systematics
  - jet E-scale improves for high P_T jets
  - clean event kinematics, separate completely t and $\bar{t}$ hemispheres
- enough statistics: ~17.4 pb
- selection cuts:
  - isolated lepton: P_T>30 GeV, $|\eta|$ < 2.5
  - E_T^{miss} > 20 GeV
  - ≥ 1 b-jet lepton hemisphere
    - R = 0.4; P_T > 20 GeV, $|\eta|$ < 2.5
  - ≥ 3 jet (1 b-jet) lepton opposite hem.
    - R = 0.2; P_T > 20 GeV, $|\eta|$ < 3.0
- W reconstruction (m_{jj})
  - use the two highest P_T non b-tagged jets

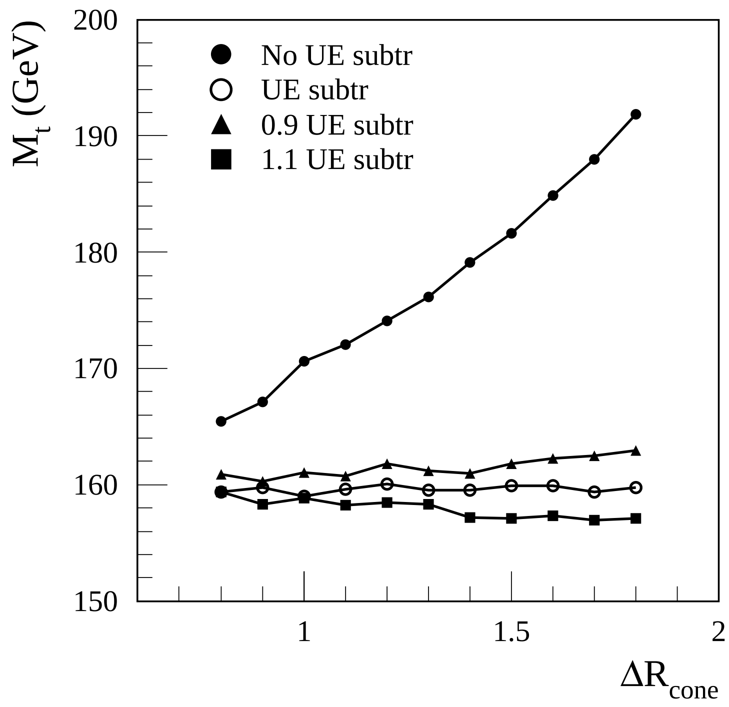
- Top reconstruction (m_{jjb})
  - combine with highest P_T b-jet
  - require P_T(jjb) > 150 GeV and $|\eta|$<2.5
  - compute direction of m_{jjb}
- use the m_{jjb} direction and compute the invariant mass of all the cells within a distance $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$



...Top mass measurement - single lepton + jets channel

... High P_T (>200 GeV) sample

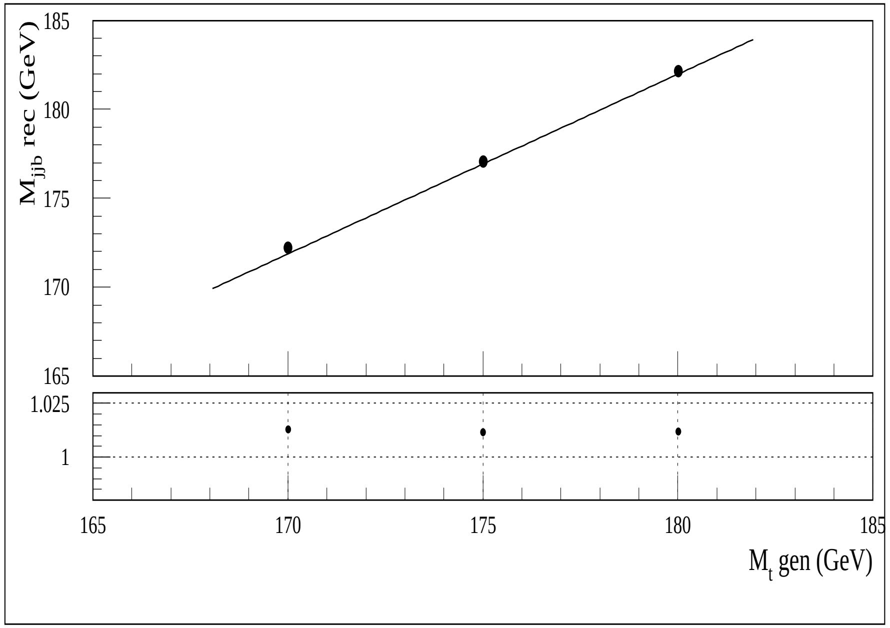
- expected strong dependence of m_{cone} with the cone size
  - underlying event and ISR contribution
  - not complete containment
- estimate the $<E_T>$ from the UE
  - use cells far away from the jets: R > 1.0
  - calculate average for all the cells
  - value used: $<E_T>/\text{cell} = 0.428$ GeV
- after UE subtraction:
  - inv. mass independent of cone size
  - lower value: $<m_{cone}> \sim 160$ GeV
  - need to re-scale to the top mass?



...Top mass measurement - single lepton + jets channel

... High P_T (>200 GeV) sample

- apply the same method to the W(→jj) from the top sample
- use the reconstructed m_w to re-scale
- after rescaling the resulting value is ~ 1.1% higher than the generated m_t
- work in progress to refine the UE estimate



- better(different) systematics with this method than jet invariant mass

but

- also important to estimate possible detector effects in the large cone used
  - electronic noise for example...

...Top mass measurement - single lepton + jets channel

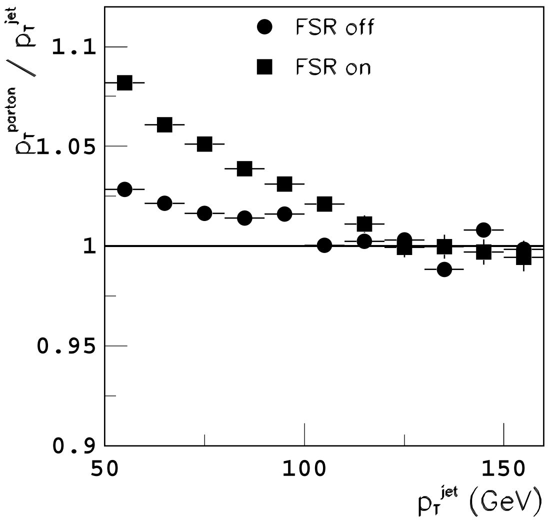
Systematic errors - studies performend

- **Jet energy scale**
  - for the light quark jets can be corrected using the constraint of the W mass
  - the problem remains for the b-jets
  - estimate error by varying ± 1% the absolute energy scale
- **b-jet fragmentation**
  - precise knowledge from LEP studies
  - vary ε_b within its error: 0.006 ↔ 0.0035
- **Initial state radiation and Multiple Interactions**
  - switch on/off in the generator
    - error estimate ⇒ 20% of the mass shift
  - a pessimistic approach, it will be better known and measured with the data
- **Final state radiation**
  - switch on/off in the generator
    - error estimate ⇒ 20% of the mass shift
  - select samples with more jets or applying jet veto
- **Combinatorial background**
  - vary background shape for the fit in the invariant mass distributions

...Top mass measurement - single lepton + jets channel

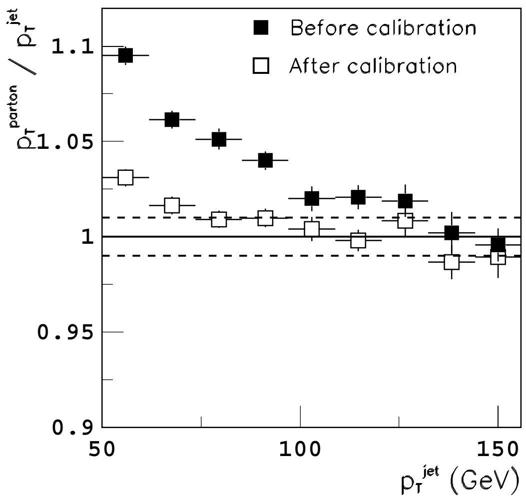
Jet Calibration

- Jets can be miss-measured because:
  - algorithm: collect the energy in a cone
    - $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} < 0.4$ (0.7)
    - energy swept away by magnetic field
    - energy from jet produced at large angle
  - other losses in the detector
    - cracks, ν, leakage
  - energy into cone from UE event or other jets
  - calorimeter response to low energy hadrons
- In-situ method for the energy calibration
  - use the known value from m_W to calibrate the light quark jets
  - use other samples for the b-jet calibration (eg. Z+jet events)



using W→ jj decays (from the top events)

...after rescaling to $m_{jj} = m_W$

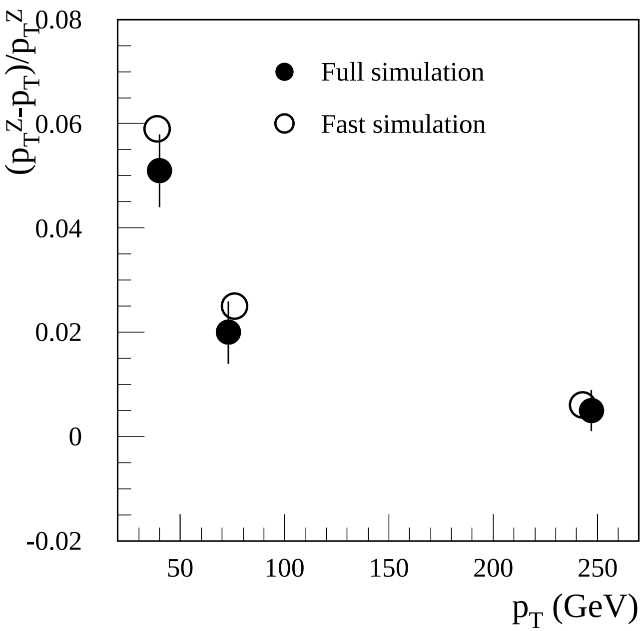


...Top mass measurement - single lepton + jets channel

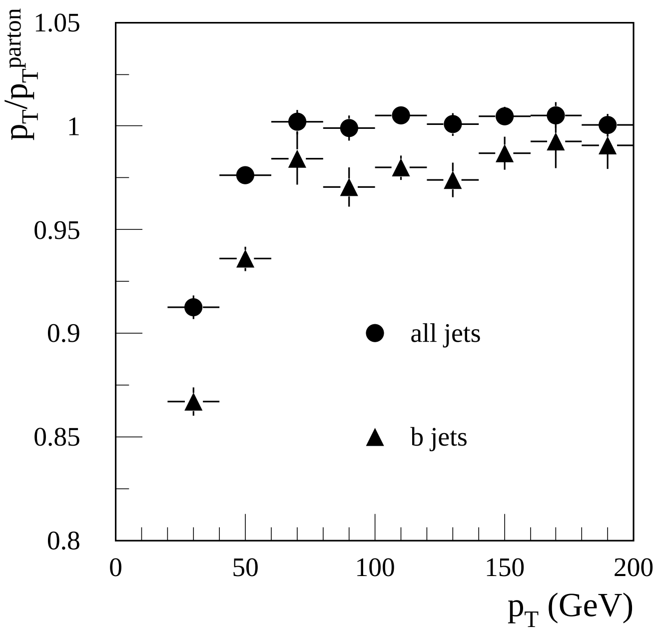
Z+jet sample

- large rate, good coverage in rapidity
- can be used for calibrating the b-jets as well
- ±1% scale can be achieved for jets with P_T > ~50 GeV (R=0.7)

Average fractional P_T imbalance Z- jet



b-jets: Reconstructed P_T^{jet} vs P_T^{parton}



...Top mass measurement - single lepton + jets channel

Inclusive sample - errors

ΔR = 0.7	δm_{top}(GeV) Standard method	Kinematic fit
FSR	1.2	1.5
ISR	0.3	0.1
Light quark jet calibration	0.3	0.4
b-jet calibration	0.7	0.6
b-quark fragmentation	0.3	0.1
Background shape	0.2	0.2
Statistical	<0.07	0.1
Total	~1.5	1.7

High P_T sample - errors

	Cone size R=1.3 δm_{top}(GeV)
Cell E-scale	0.6
b-quark fragmentation	0.1
ISR	0.1
FSR	0.1
Calibration method (re-scaling, W→jj decays)	1.6
Total	≥1.72

- the larger contribution comes from the final state radiation
  - we used the 20% of the m_t shift when the FSR is switched ON/OF
- the contribution from the light quark jet E-scale calibration can be further reduced if the jets are re-scaled using the m_W constraint
- in the high P_T sample the largest contribution comes from the rescaling
  - work in progress to understand it better

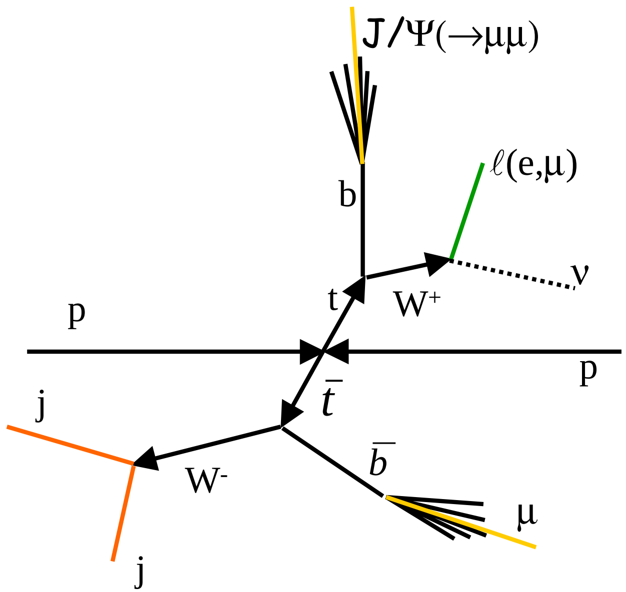
An overall systematic error ~2GeV seems feasible. Reducing it further will require much more effort but not impossible

- eg. preliminary estimates when jet adjustment is applied in the kinematic fit method indicate an error of ~1.3GeV

... Top mass measurement - multi-lepton channel

m_t from $t \to \ell + J/\Psi + X$ decays (CMS)

- interesting sub-sample
  - much stronger correlation to m_t due to large mass of J/Ψ
  - cleaner sample due to the presence of J/Ψ in the final state
- selection cuts:
  - isolated-ℓ: $p_T > 15$GeV, $|\eta| < 2.4$
  - 3 non isolated-μ: $p_T > 4$ GeV, $|\eta| < 2.4$
    - two of them having $m_{\mu\mu} \sim m_{J/\psi}$
  - $|m_{\ell\ell} - m_Z| > 10$ GeV; $E_T^{miss} > 40$ GeV
  - two additional jets: $p_T > 15$ GeV
- event yields/1 year @ 10^{34} (100 fb^{-1})
  - ~1000 events assuming
    - ~8% trigger + reconstruction efficiency



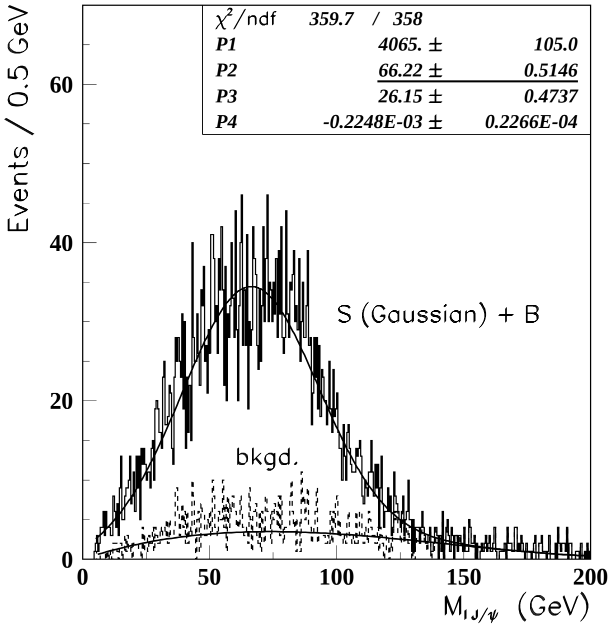
- possible extensions:
  - use the $b \to J/\Psi \to e^+e^-$ channel as well for low luminosity
  - use jet-charge method instead of the W semi-leptonic decay

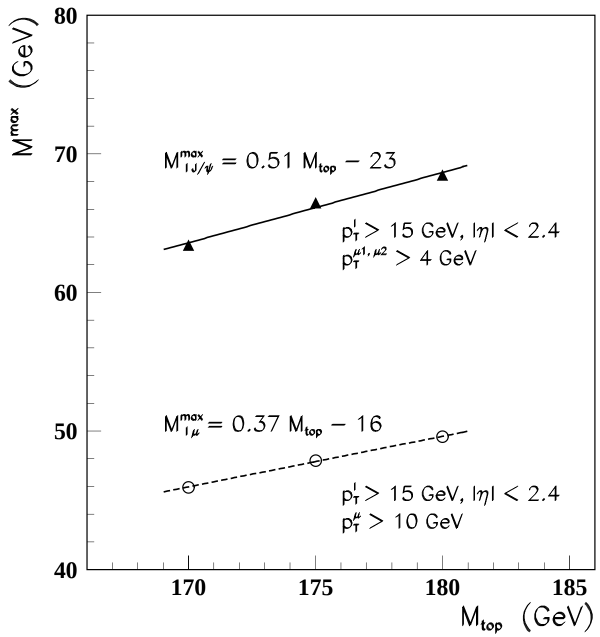
$\to$ work is in progress...

... Top mass measurement - multi-lepton channel

$L_{\text{int}} = 300 \text{fb}^{-1}$

Correction between $m_{\ell J/\Psi}$ and m_{top}

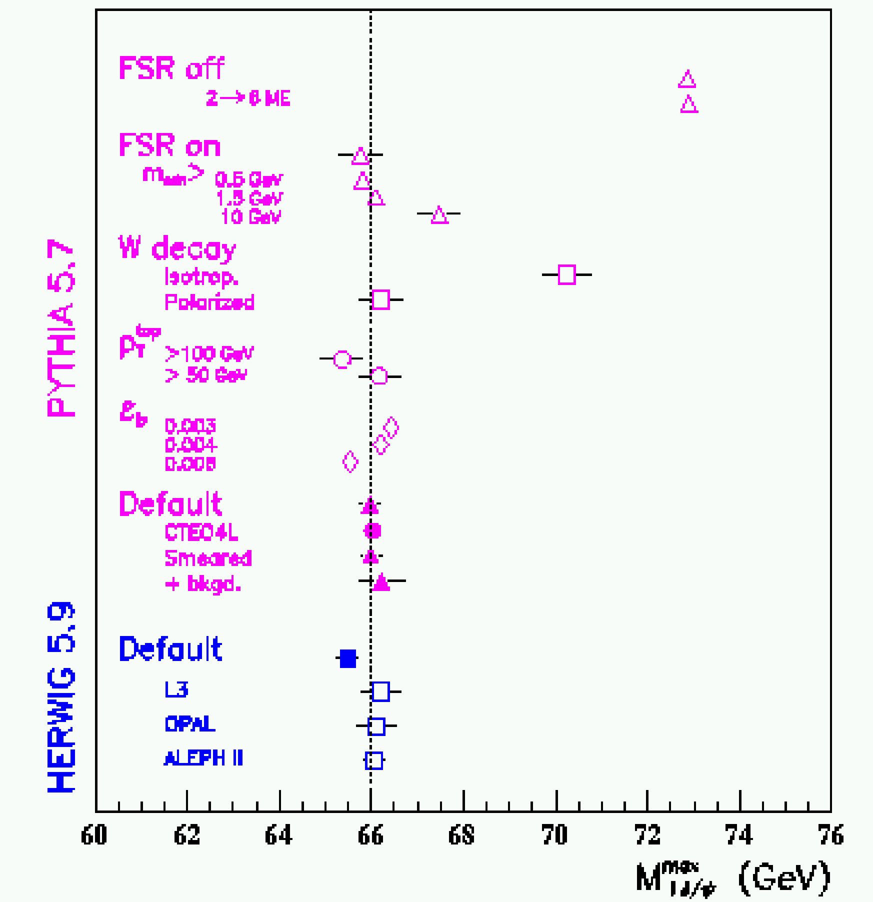




- background due to wrong assignment of the decay topology
  - ~30%, can be verified with data

... Top mass measurement - multi-lepton channel

Systematic uncertainties



- Quite stable for reasonable choice of parameters
- PYTHIA and HERWIG expectations are within $\lesssim$ 0.5 GeV
  - can be taken as an estimate of the systematics in the models
  - this translates to $\delta m_t \lesssim 1$ GeV

It might be possible to reach a systematic uncertainty of $\lesssim$ 1 GeV !

Single top physics

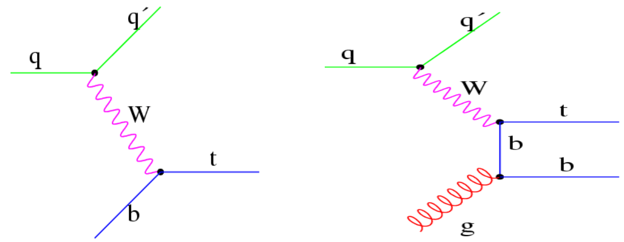
Physics interest

- measure $|V_{tb}|$, $\Gamma(t \rightarrow Wb)$ in SM
- probe of coupling at W-t-b vertex
- good sensitivity to polarization effects
  - also sensitive to anomalous couplings, CP violation, etc...
- overall single-top production cross-section at LHC: > 300pb
- possible to detect them in all major channels

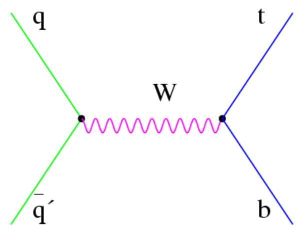
$\Rightarrow$ for details see talk of D. ONeil

Single top production at LHC

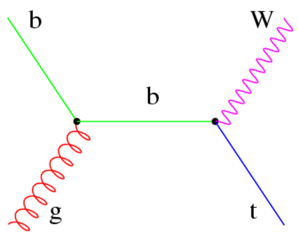
- W-gluon fusion ($\sigma \cong 250$pb)



- s-channel (W*) ($\sigma \cong 10$pb)



- Wt ($\sigma \cong 60$pb)

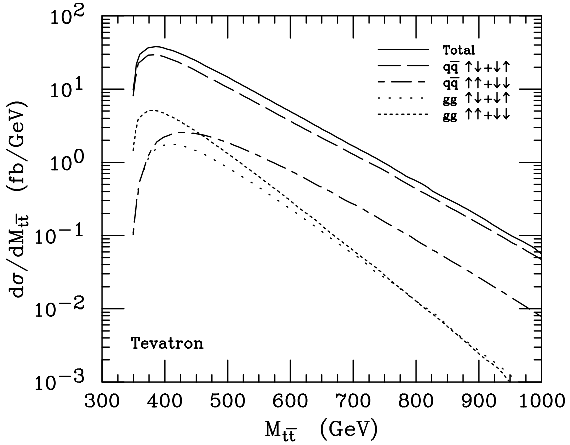


Spin correlation and CP violation

- in SM with $m_t \cong 175\text{GeV}$
- $\Gamma(t) \cong 1.4\text{GeV} \gg \Lambda_{QCD}$
  - t quark decays before hadronization
    - spin properties could be studied via decay products
- top helicity/spin affect the angular distribution of the daughter particles

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i \cos\theta_i\right)$$

ℓ, d, s: α=1
ν, u, c: α=-0.31
b: α = -0.40



G.Mahlon - S.Parke
hep-ph/9512264

- the $t\bar{t}$ spin correlation appears in the angular distribution of the top decay products in the $t\bar{t}$ frame:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i \cdot d\cos\theta_j} = \frac{1}{4}\left(1 - \kappa\cos\theta_i\cos\theta_j\right)$$

$$\kappa = A\alpha_i\alpha_j, \qquad A = \frac{N_{LL,RR} - N_{LR,RL}}{N_{LL,RR} + N_{LR,RL}}$$

- the asymmetry depends on the t production mode:
  - qq annihilation $\rightarrow$ opposite helicity
  - gg fusion $\rightarrow$ same helicity
- LHC: ~90% gg fusion

  $\Rightarrow$ the majority of t have the same helicity

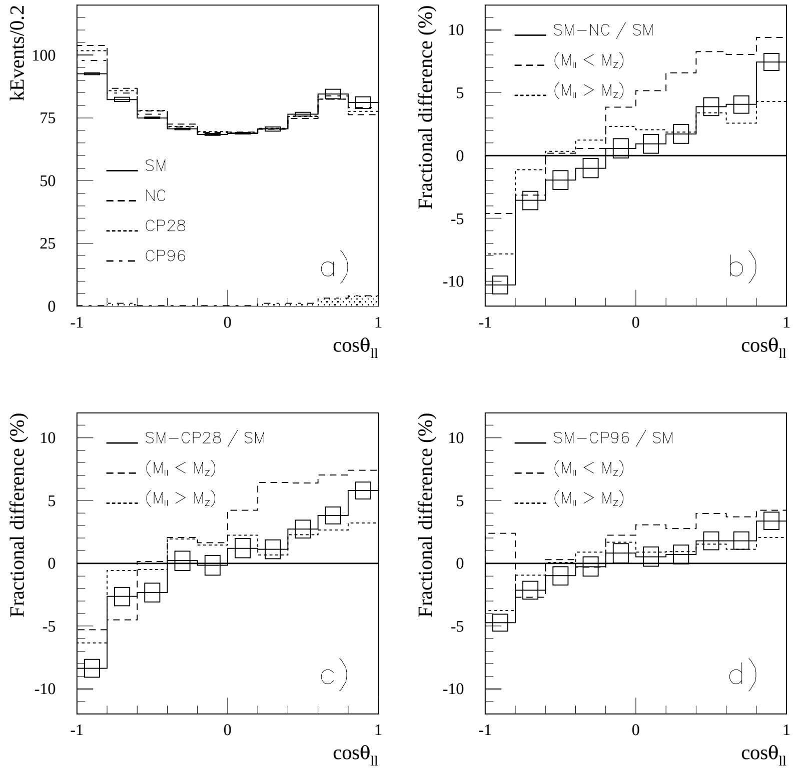
  $A_{SM} = 0.33 \pm 0.01(\text{stat})$
  PYTHIA, 10^6 di-lepton events

... Spin correlation and CP violation

Modification in PYTHIA to include $t\bar{t}$ spin correlations & CP-violation in top production and decay

di-lepton event sample

- selection cuts:
  - two isolated leptons
    - p_T>35, 30 GeV, $|\eta|$<2.5
  - $|m_{\ell\ell} - m_Z|$>10 GeV; E_T^{miss} > 40 GeV
  - two additional jets: p_T >15 GeV
- background:
  - DY+jets, Z($\rightarrow\tau\tau$) +jets, WW+jets, b
  - S/B = 7.8, ε~31.5%
    - S/B = 50, ε~23% including b-tagging
- work in progress to use the single-lepton+jets channel
  - much more statistics, but also background



- estimated systematic error

  A_{SM}= ±0.03

  preliminary estimate, work ongoing...

Top quark (rare) decays

- In SM: Br(t→Wb) ≅ 99.9% , Br(t→Ws) ≅ 0.1%, Br(t→Wd) ≅ 0.01%
- Any other decay is rare and most probably a probe for new physics!

Br(t→bX), measurement of $|V_{tb}|$

- compare rates of single & double b-tag top events:

$$R_{2b/1b} = Br(t \to Wb)/Br(t \to Wq) = |V_{tb}|^2 / \left(|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2\right) = |V_{tb}|^2$$

  - assuming 3-generations and unitarity of CKM matrix
- CDF: $R_{2b/1b}=0.99\pm0.25 \to |V_{tb}|>0.76$
- LHC (10 fb^{-1}):
  - 820(276)K single(double) tag $t\bar{t}$ events

  → $\delta R_{2b/1b}/ R_{2b/2b}$ (stat) ≅ 0.2%

  systematics from b-tag efficiency and fake rate will dominate

Br(t→WX)

- in SM: $R_{\ell\ell/\ell} = Br(W \to \ell\nu) = 2/9$
- at LHC (10 fb^{-1})
  - 443(46) K single(double) lepton top events

  → $\delta R_{\ell\ell/\ell}/ R_{\ell\ell/\ell}$ (stat) ≅ 0.5%

  again systematics will dominate

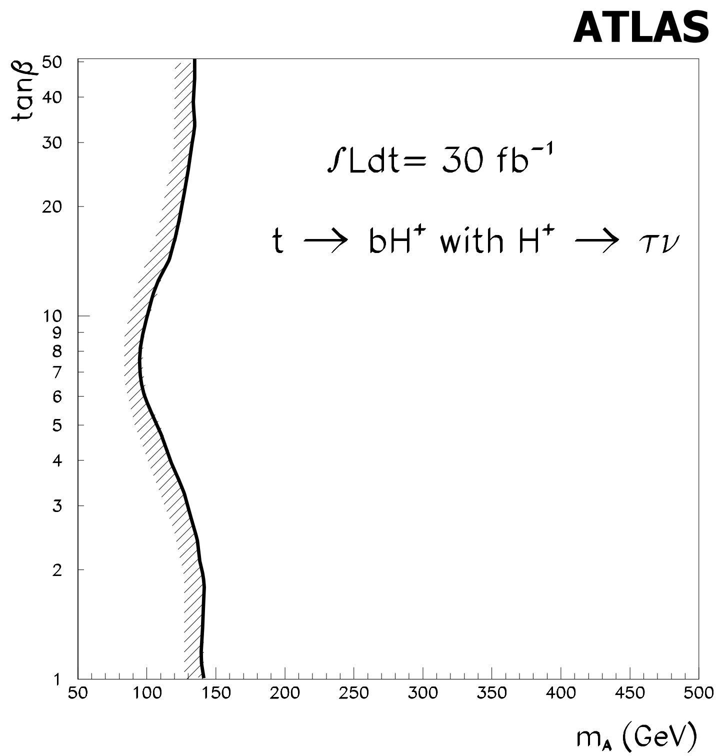
Radiative decays: t→WbZ, t→WbH

- very sensitive to m_t, but
- sensitivity @10fb^{-1}: Br(t→WbZ)~10^{-3}
  - even at high luminosity above the SM prediction of 10^{-7} -10^{-6}
- t→WbH hopeless as well

...Top quark (rare) decays

$t \to H^+b$, $H^\pm \to \tau\nu$

- look for excess in the τ lepton rate in $t\bar{t}$ events
  - single prong τ– lepton identification
- main backgrounds:
  - $t\bar{t}$ events with $t\bar{t} \to WbWb \to \tau\nu_\tau b\ell\nu b$
    - can be supressed using the τ polarization effects - CMS
      - $\pi^\pm$ p_T spectrum harder in $H^\pm$decays than from $W^\pm$
  - W+jet events with $W \to \tau\nu_\tau$
    - b-tag a major asset
- ATLAS results:
  - m_{H+}=130GeV, $\tan\beta$ = 5
    - S = ~1200 τ events ;
    - B = ~2500 τ-leptons from W-decay
    - = ~3400 fake τ-leptons
- important systematics: τ-id, fakes...



- CMS results: (5σ discovery, 10fb^{-1})
  - m_A<110GeV for all $\tan\beta$ values, extended to m_A<140 GeV for small or large $\tan\beta$

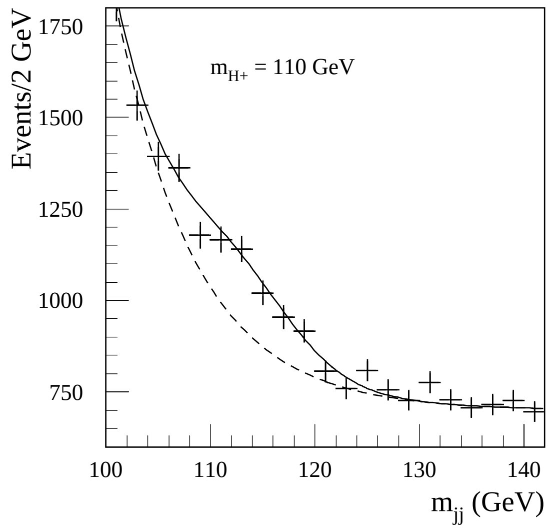
...Top quark (rare) decays

$t \to H^+ b$, $H^\pm \to cs$

- could reconstruct the Higgs mass
- production rates:

$t\bar{t}$ **with** $t \to Wb$, $W \to l\nu$ $t \to H^+ b$, $H^+ \to cs$	$t\bar{t}$ **with** $t \to Wb$, $W \to l\nu$ $t \to Wb$, $W \to jj$
m_{H+}=110GeV $\sigma \times Br$ = 1.7pb	$\sigma \times Br$ = 170pb
m_{H+}=130GeV $\sigma \times Br$ = 0.7pb	$\sigma \times Br$ = 90pb

- selection cuts:
  - isolated high p_T lepton (top decay)
  - only two b-taged jets p_T>15 GeV
  - two non-b central jets ($|\eta|$<2.0)
    - and no other jet with p_T>15 GeV in this central region
- complementary to the $H^\pm \to \tau\nu$ channel for low $\tan\beta$ values



m_{H^+} (GeV)	110	130
Signal	870	430
Background	18 000	10 000
S/B	4.8%	4.5%
$S/\sqrt{B}$	6.5	4.4

...Top quark (rare) decays

Flavor Changing Neutral Currents

- strongly suppressed in SM ($<10^{-10}$)
  - any observation would be sign of new physics

$t \rightarrow$ Zq (CMS)

- reconstruct $Z \rightarrow ll$ channel
  - leptons: $p_T>20$ GeV, $|\eta|<2.5$
  - $|m_{ll} - m_Z|<6$ GeV
- combine both "hadronic" and "leptonic" top decay modes
- background:
  - Z+jets, W+Z, $t\bar{t}$ Z

  can be reduced even to zero level by tight cuts
- overall sensitivity
  - $Br(t \rightarrow Zq) \sim 10^{-4}$ for 100 fb^{-1}

$t \rightarrow \gamma q(u,c)$ (CMS)

- suffers from large QCD background
- selection cuts:
  - isolated γ: $p_T>75$ GeV, $|\eta|<2.5$
  - isolated lepton: $p_T>15$ GeV, $|\eta|<2.5$
  - $\geq$2 jets with $p_T>30$ GeV
  - reconstruct both top quarks
    - γ–jet: $m_{\gamma jet} = m_t \pm 15$ GeV; jet no b-tag
    - $l\nu b$: $m_{l\nu b} = m_t \pm 25$ GeV; jet b-tag
  - veto other jets with $p_T>50$ GeV
- results:
  - 270 background events ($t\bar{t}$,W+j) @100fb^{-1}
  - S/B ~ 1 for $Br(t \rightarrow \gamma q(u,c)) = 10^{-4}$
- 5σ discovery**:**3.4×10^{-5} for 100 fb^{-1}

Summary

- An overview of the top studies performed by both experiments ATLAS and CMS has been presented here
- A broad spectrum of top physics has been studied so far in the context of the TDR (ATLAS) and of the LHCC SM Workshop (ATLAS+CMS)
- The importance of top physics at LHC is very much acknowledged
  - top is a critical tool in both to understand the SM physics but also as an important background for many new physics searches beyond that
  - in addition, it is an important tool to understand and tune the detector performance and in particular the jet E-scale calibration
- Before LHC turns on, results from the Tevatron Run-II will be available which will be an important guide

- we are looking very forward for the LHC startup at $\geqq$ 2005

new exciting physics might be just about to show up ...